# UAV Trajectory Modeling Using Neural Networks

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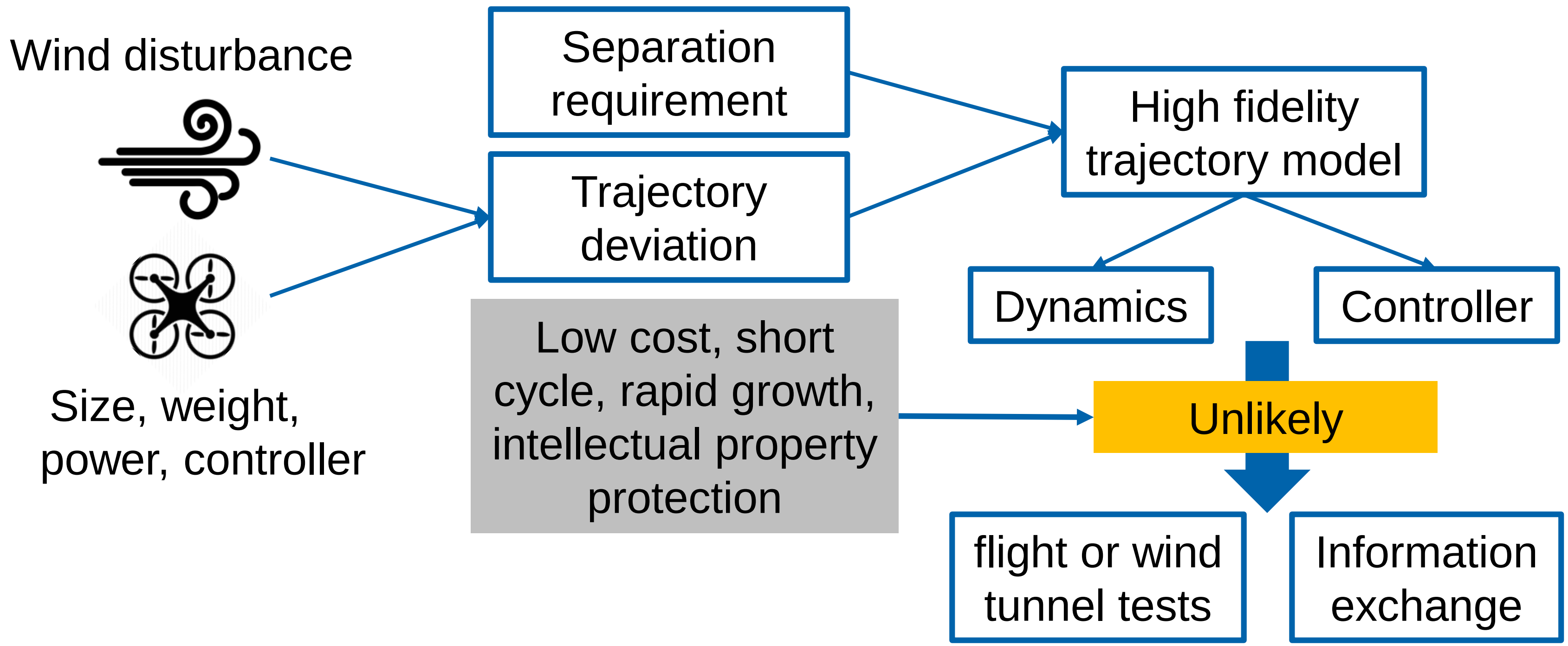
# Motivation

Trajectory models are required for traffic management study




**Objective:** Study the feasibility of modeling trajectory using Neural Networks

# Outline

- Approach
  - General trajectory model
  - Neural Network method
- Experiment
- Summary

# Conventional Trajectory Model

Dynamics

Controller

Moment

$$\begin{bmatrix}\dot{p}\\\dot{q}\\\dot{r}\end{bmatrix}=\begin{bmatrix}\frac{J_y-J_z}{J_x}qr\\\frac{J_z-J_x}{J_y}pr\\\frac{J_x-J_y}{J_z}pq\end{bmatrix}+\begin{bmatrix}\frac{1}{J_x}M_\phi\\\frac{1}{J_y}M_\theta\\\frac{1}{J_z}M_\psi\end{bmatrix}$$

Kinematic

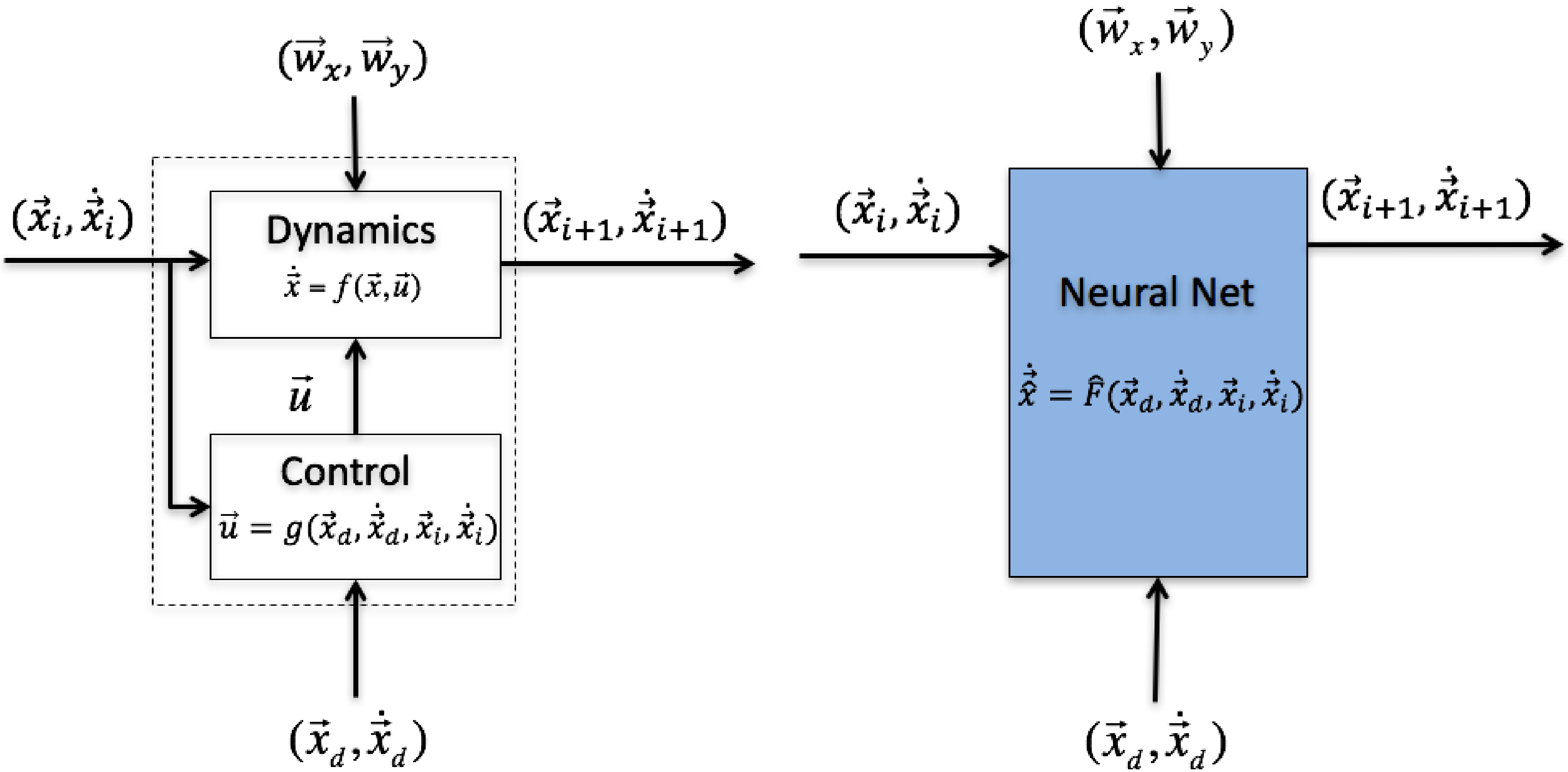
$$\begin{bmatrix}\dot{\phi}\\\dot{\theta}\\\dot{\psi}\end{bmatrix}=\begin{bmatrix}1 & \sin\phi\tan\theta & \cos\phi\tan\theta\\0 & \cos\phi & -\sin\phi\\0 & \frac{\sin\phi}{\cos\theta} & \frac{\cos\phi}{\cos\theta}\end{bmatrix}\begin{bmatrix}p\\q\\r\end{bmatrix}$$

Force

$$\begin{bmatrix}\dot{u}\\\dot{v}\\\dot{w}\end{bmatrix}=\begin{bmatrix}rv-qw\\pw-ru\\qu-pv\end{bmatrix}+\begin{bmatrix}-g\sin\theta\\g\cos\theta\sin\phi\\g\cos\theta\cos\phi\end{bmatrix}+\frac{1}{m}\begin{bmatrix}F_x\\F_y\\F_z\end{bmatrix}$$

$$\begin{bmatrix}\dot{x}\\\dot{y}\\\dot{z}\end{bmatrix}=\begin{bmatrix}c\theta c\psi & s\phi s\theta c\psi-c\phi s\psi & c\phi s\theta c\psi+s\phi s\psi\\c\theta s\psi & s\phi s\theta s\psi+c\phi c\psi & c\phi s\theta s\psi-s\phi c\psi\\s\theta & -s\phi c\theta & -c\phi c\theta\end{bmatrix}\begin{bmatrix}u\\v\\w\end{bmatrix}$$

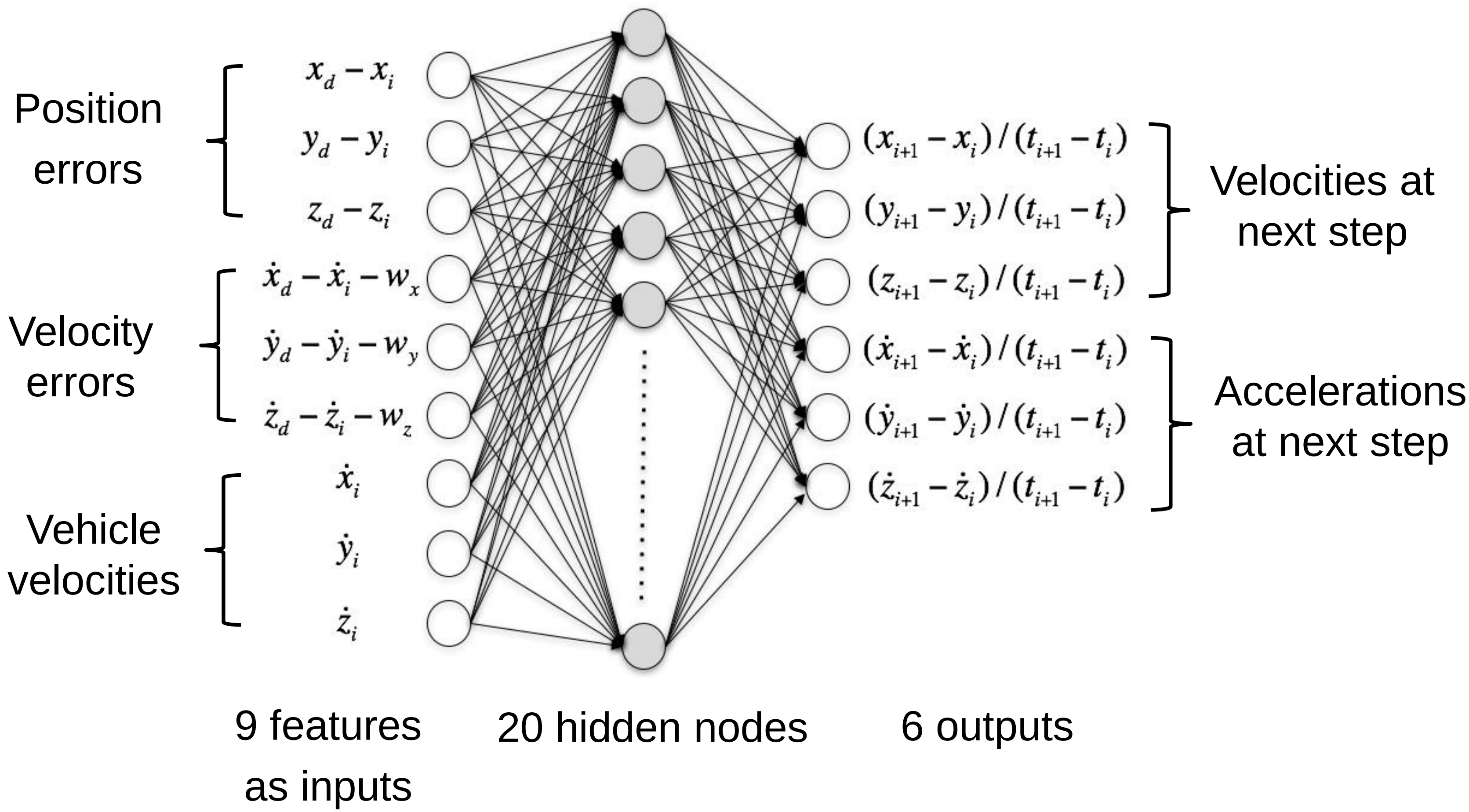
# Neural Network Trajectory Model




NN captures both dynamics and controller

# Neural Network Structure

Multiple Layer Perceptron (MLP) Neural Network



# Outline

- Approach
- Experiment
  - Data generation
  - Training
  - Trajectory prediction
- Summary

# Data generation – Quadrotor trajectory model

Dynamics:

$$\begin{bmatrix} \dot{x} \\ \ddot{x} \\ \dot{y} \\ \ddot{y} \\ \ddot{z} \\ \ddot{\phi} \\ \ddot{\theta} \\ \ddot{\psi} \end{bmatrix} = \begin{bmatrix} \dot{x} + \omega_e \\ -(\cos\phi \sin\theta \cos\psi + \sin\phi \sin\psi) F_z/m \\ \dot{y} + \omega_n \\ (-\cos\phi \sin\theta \sin\psi + \sin\phi \cos\psi) F_z/m \\ -g + \cos\phi \cos\theta \, F_z/m \\ M_\phi/J_x \\ M_\theta/J_y \\ M_\psi/J_z \end{bmatrix}$$

Controller: [proportional-derivative (PD)]

$$\begin{bmatrix} \ddot{x} \\ \ddot{y} \end{bmatrix} = \begin{bmatrix} k_p(x_d - x) + k_d(\dot{x}_d - \dot{x}) \\ k_p(y_d - y) + k_d(\dot{y}_d - \dot{y}) \end{bmatrix}$$

$$\begin{bmatrix} \phi_d \\ \theta_d \end{bmatrix} = \frac{m}{F_z} \begin{bmatrix} -\sin\psi & -\cos\psi \\ \cos\psi & -\sin\psi \end{bmatrix}^{-1} \begin{bmatrix} \ddot{x} \\ \ddot{y} \end{bmatrix}$$

$$\begin{bmatrix} M_\phi \\ M_\theta \end{bmatrix} = \begin{bmatrix} k_{p,\phi}(\phi_d - \phi) + k_{d,\phi}(\dot{\phi}_d - \dot{\phi}) \\ k_{p,\theta}(\theta_d - \theta) + k_{d,\theta}(\dot{\theta}_d - \dot{\theta}) \end{bmatrix} l$$

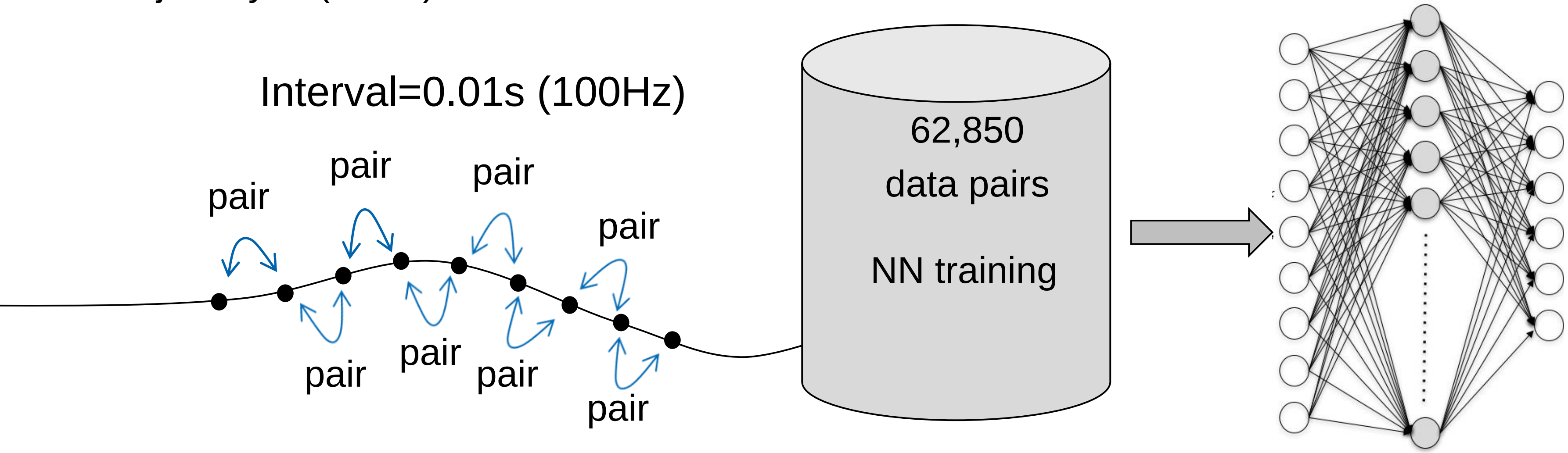
$$k_{p,\phi} = 4.5, k_{d,\phi} = 0.5, k_{p,\theta} = 4.5, k_{d,\theta} = 0.5, k_p = 7.5, k_d = 4.2$$

# Training Setup

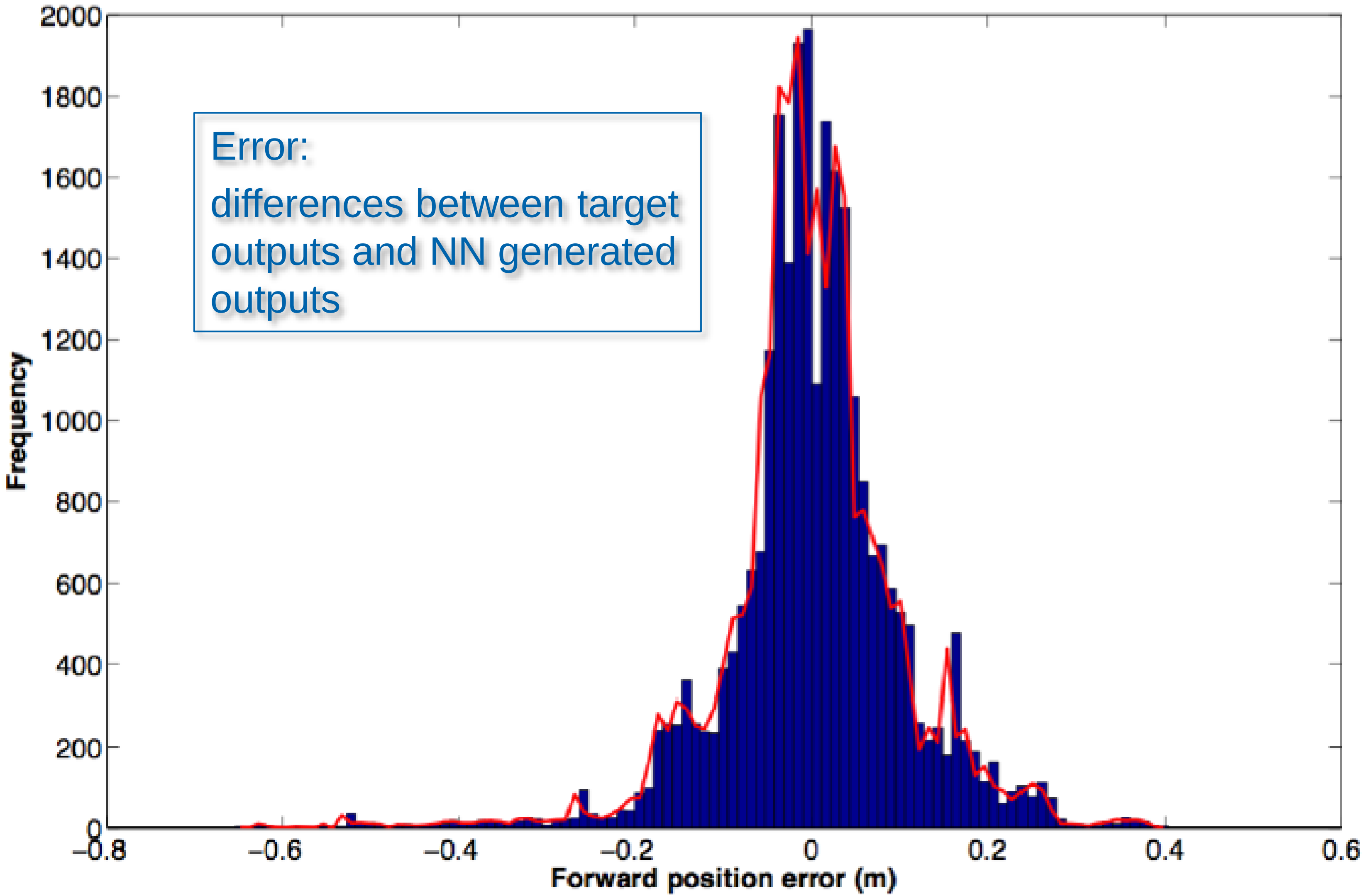
Total 35 trajectories in horizontal plane:

| **Parameters** | **Values** | **Units** |
|---|---|---|
| Desired ground speed | 2,5,8,11,12,13,14,15 | m/s |
| Cross wind speed | 3-5 selected values in [1.0, 9.5] | m/s |

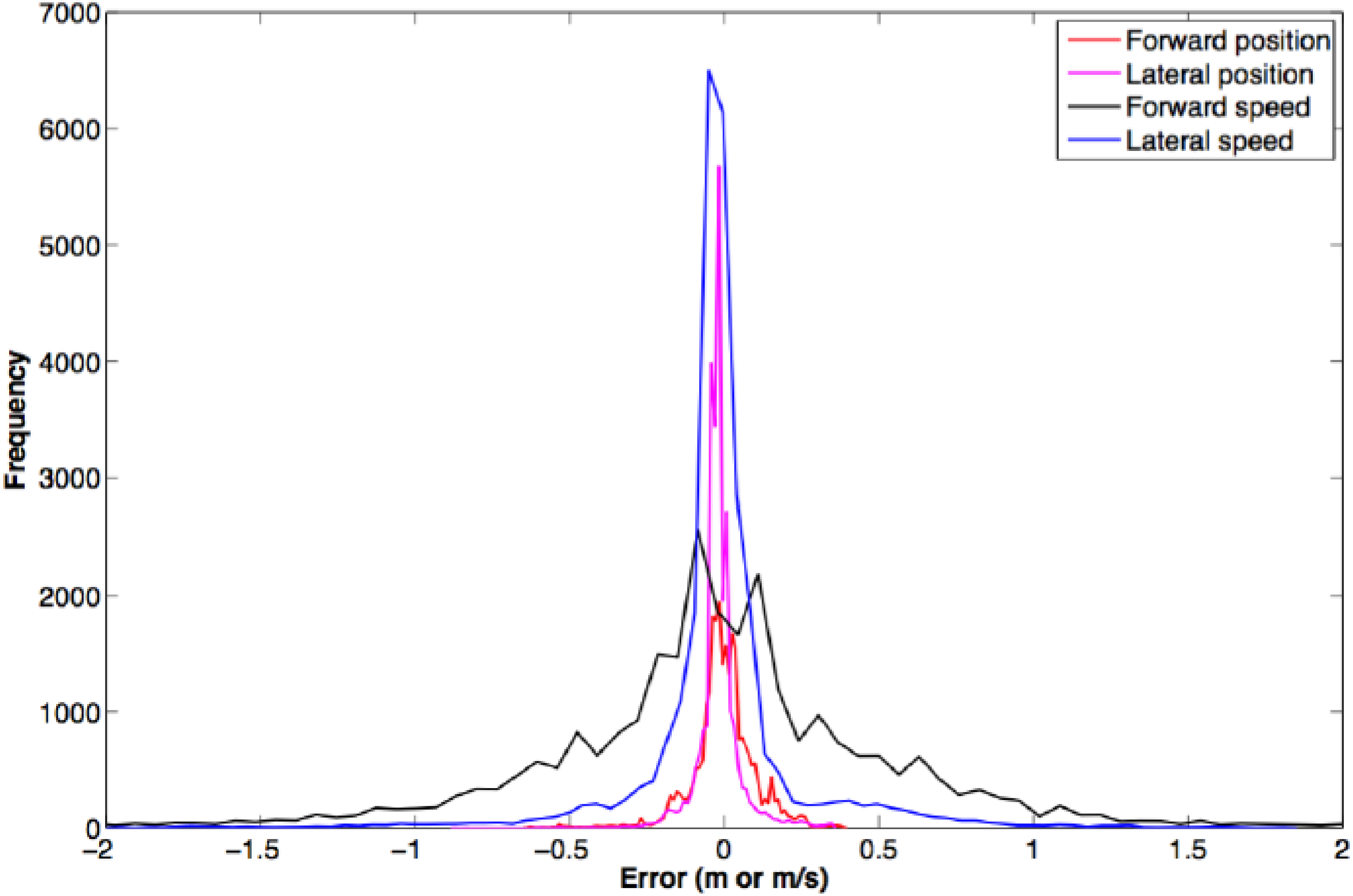
Trajectory #i (~20 s):



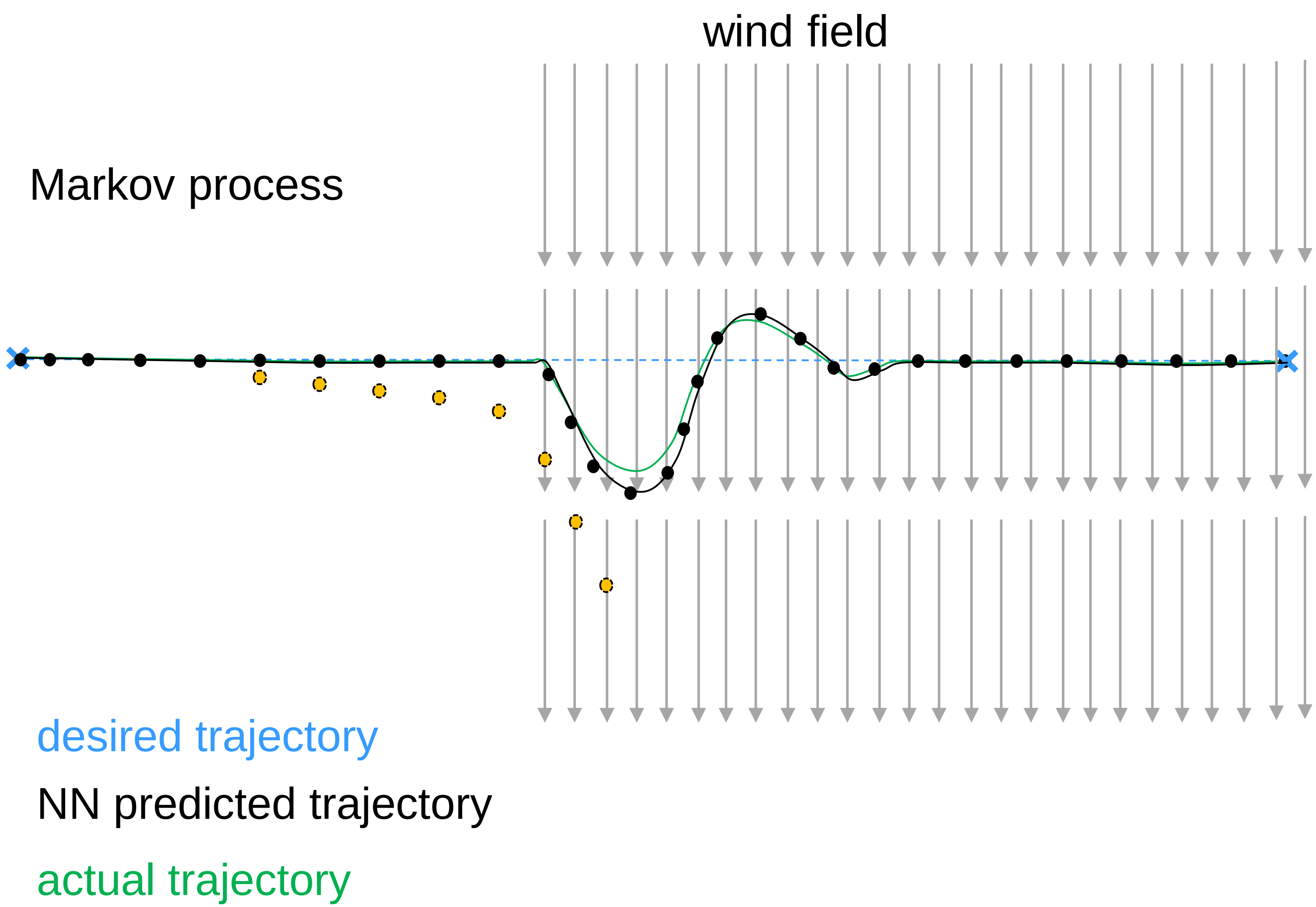
# Training Performance: Forward-position Errors



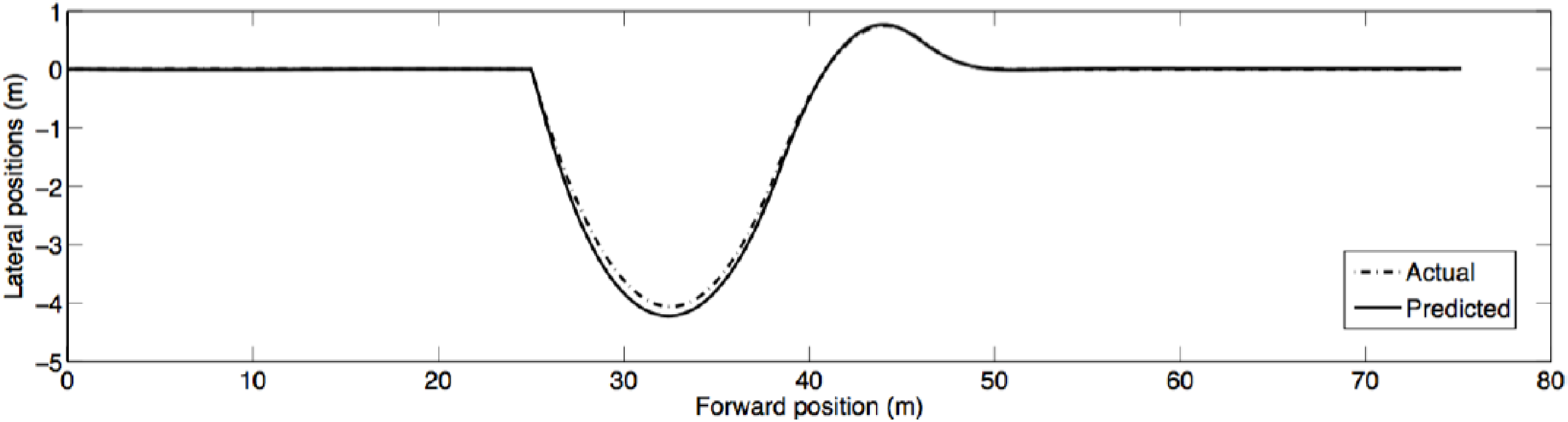
# Training Performance: All Output Errors

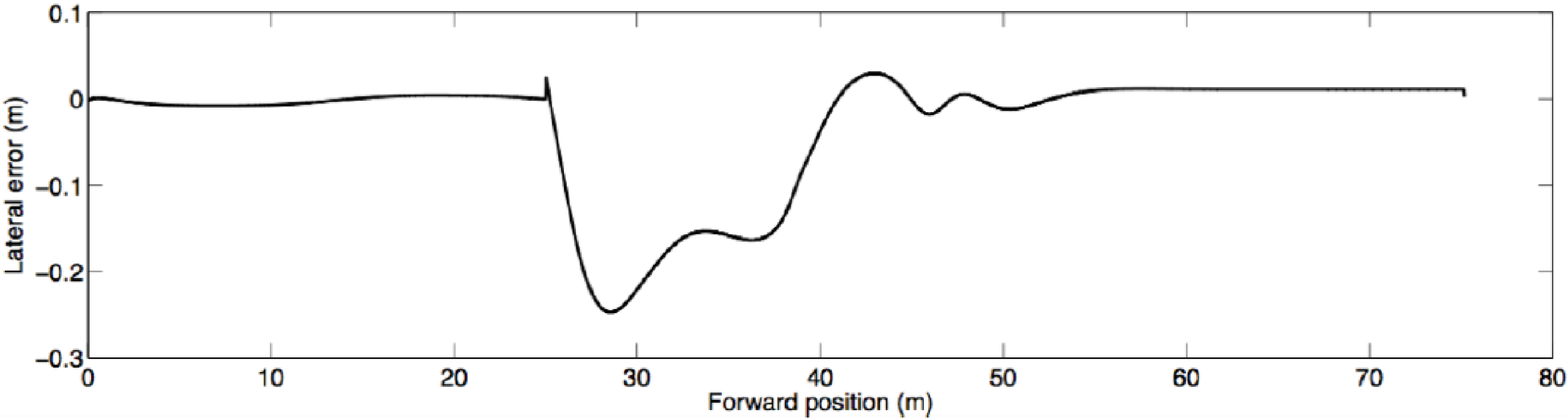


# Trajectory Prediction Approach

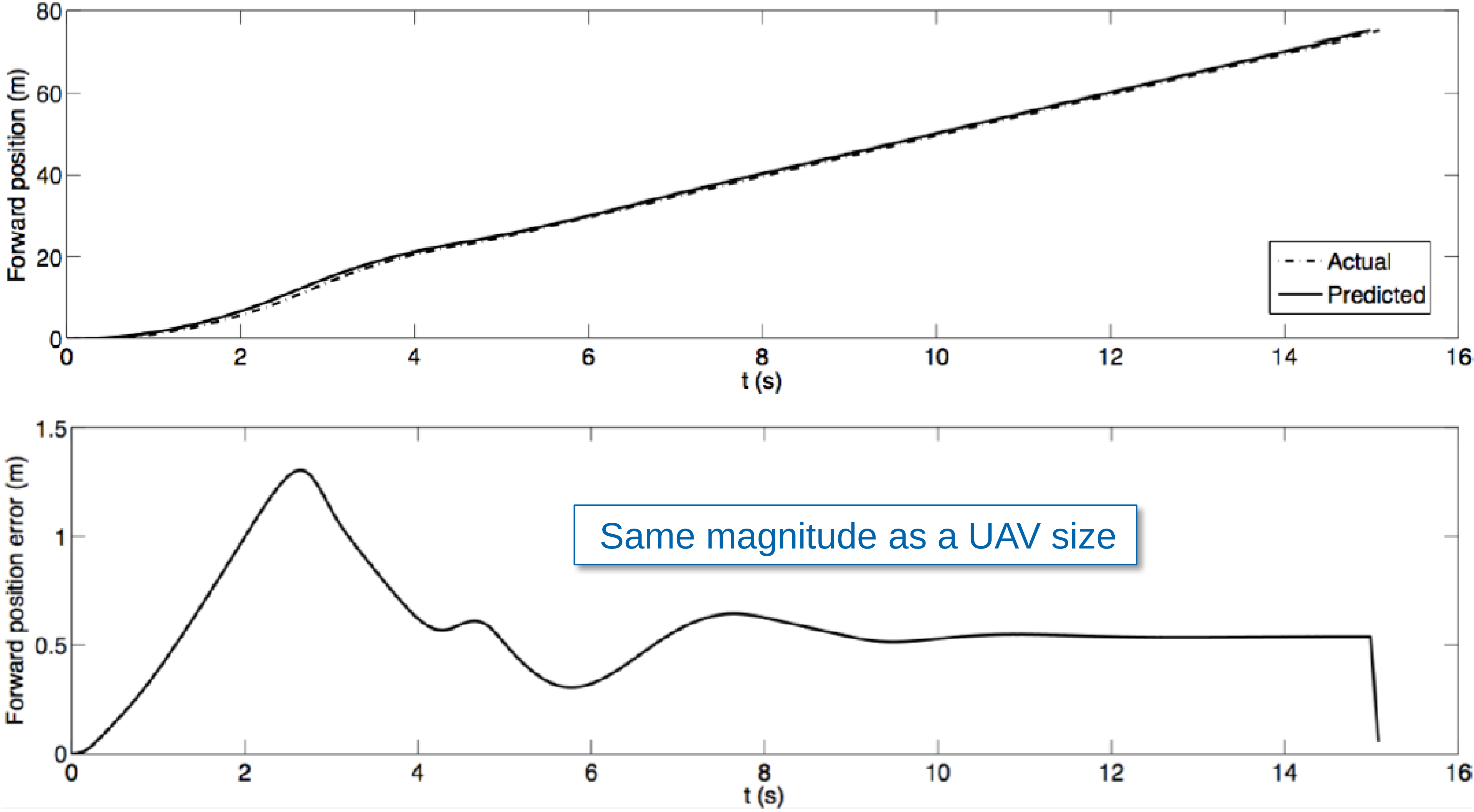


# Position Error in Spatial Dimension

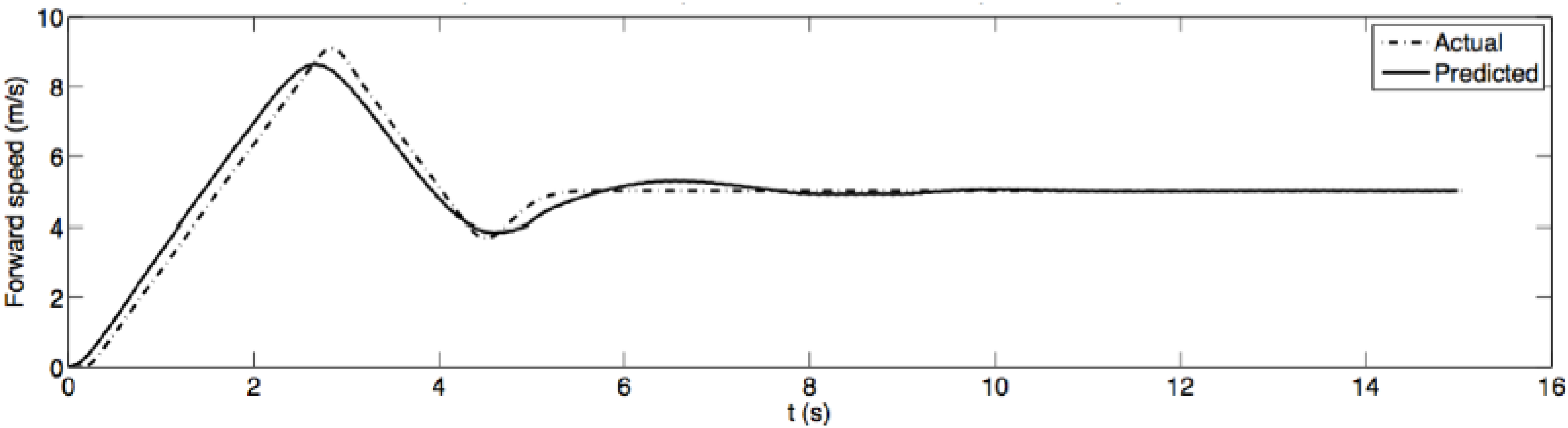


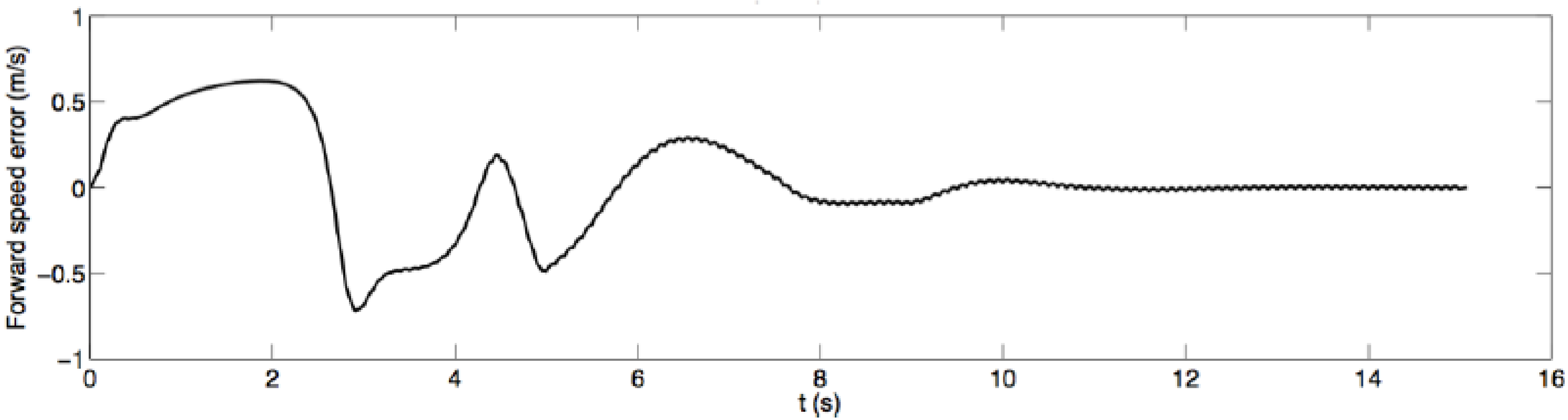



# Position Error in Temporal Dimension



# Forward Speed Error



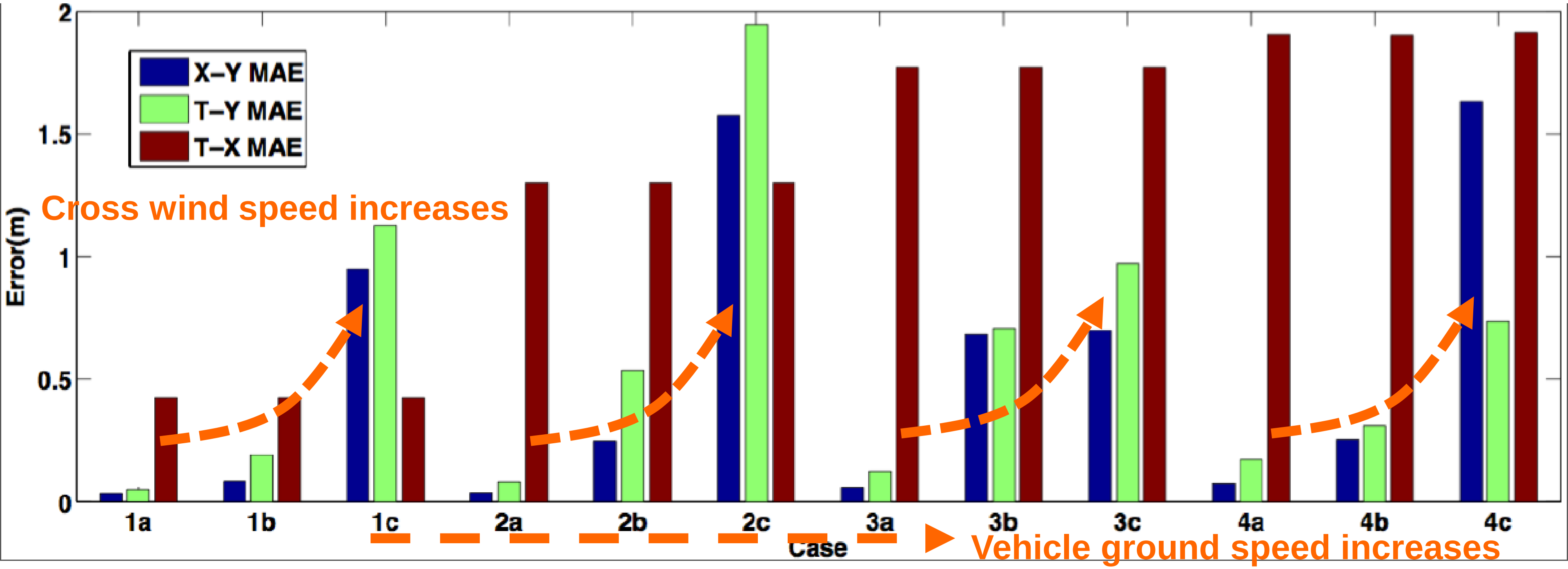
# Prediction Verification Cases

12 prediction cases:

| Case | 1a | 1b | 1c | 2a | 2b | 2c | 3a | 3b | 3c | 4a | 4b | 4c |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Vehicle ground speed (m/s) | 2.0 | 2.0 | 2.0 | 5.0 | 5.0 | 5.0 | 8.0 | 8.0 | 8.0 | 11.0 | 11.0 | 11.0 |
| Cross wind speed (m/s) | 0.7 | 2.4 | 7.5 | 0.9 | 5.0 | 8.6 | 1.4 | 6.7 | 9.5 | 1.9 | 4.0 | 9.2 |

# Prediction Verification

MAE – Maximum Absolute Error




- Forward speed error increases with the vehicle speed
- Lateral speed error increases with the cross wind speed
- All errors are smaller than 2 m
- Spatial errors are smaller than temporal errors

# Summary

- Proposed a Neural Network based approach for UAV trajectory prediction
- Conducted experiments using a sample vehicle trajectory model
- The concept is promising with the trajectory prediction accuracy of two meters

# Future Work

- Perform experiments using data collected from flight tests
- Extend the application to vertical direction
- Explore different machine learning methods and setups

# Questions?

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